REMARKS

Claims 1-65 remain in the application. Claims 66-80 are withdrawn as directed to a non-elected invention. Claim 1 has been amended to clarify the scope of the claim.

In the Office Action dated January 23, 2004, Claims 1-65 were rejected under 35 U.S.C. §112, ¶1 for lack of enablement, and Claims 1-17 were rejected under 35 U.S.C. §112, ¶2 for indefiniteness. Claims 26, 26, 28-35, 39, 40 and 42 were rejected under 35 U.S.C. §102 as anticipated by U.S. 4,473,622 to Chludinski *et al.* (Chludinski), and Claims 36 and 37 were rejected under 35 U.S.C. §103 as being obvious in view of Chludinski.

The Examiner indicated that Claims 41-43, 58 and 59 would be allowable if rewritten in independent form to include all the limitations of their respective base claims, and any intervening claims, and if the §112 enablement rejections were overcome. The Examiner also indicated that Claims 1-24, 45-57 and 60-65 would be allowable if the §112 rejections were overcome.

For the following reasons, it is believed that the Examiner's rejections are overcome, and Claims 1-65 are all allowable.

A. Enablement Rejections Under 35 U.S.C. §112, ¶1

The Examiner's rejection of Claims 1-65 for lack of enablement is respectfully traversed. In the Amendment filed on October 1, 2003, independent Claims 1, 18, 25, 28 and 45 were amended to specify, *inter alia*, that the mechanical energy recovered from the expander is in excess of the energy used to pressurize the air. The Examiner appears to believe that this limitation raises an issue as to whether the claimed system violates the fundamental law of the conversation of energy, since the Examiner believes the limitation is claiming "the conversion of thermal energy used to compress the pressurized air (via evaporation of the cooling water) into mechanical energy," where "the total energy within the domain must remain constant."

The Applicants respectfully submit that the Examiner's rejection is based on a misunderstanding of what is recited in the present claims. In the limitation at issue, the applicants intend to claim that the energy recovered by passing the steam-laden exhaust through the expander is in excess of the mechanical energy used to compress the working fluid (*i.e.* air) at

the beginning of the cycle. Applicants do not claim the complete conversion of all thermal energy into mechanical energy by evaporation of warm cooling water into the pressurized air stream, as the Examiner appears to suggest. Instead, the evaporation, or partial pressure boiling, of warm water into the pressurized air stream recovers a portion of the otherwise-wasted thermal energy of the warmed water, and the extra mass provided by this water can be converted into mechanical energy by passing the water-laden exhaust stream through the expander. Thus, because of the added energy from the evaporation of water into the pressurized air, the mechanical energy recovered at the expander is in excess of the non-trivial mechanical energy required to initially compress the air.

The Examiner is correct in noting that applicants do not intend to claim a system in violation of the First Law. The Examiner appears to express concerns regarding the statement on p. 17, lines 19-21 of the Specification, which states that "because all the heat added to drive the expander is recovered, the expander is effectively 100% efficient." However, it is believed that the Examiner's concerns regarding this statement can be allayed with a brief explanation of some of the principles of the claimed invention.

In the present system, the efficiency of the fuel cell is in the general range of 50%, and the recovery of waste heat from the fuel cell into the turbine amounts to about 50% recovery of the waste heat as mechanical energy. This is about 25% of the entire energy of the system, although it is diminished by the energy needed to compress the air, and in a real system, by various other parasitic loads. The following description is intended to clarify the description in the specification.

As discussed above, the source of the energy that produces the excess of power output over the power needed to compress the air is the heat energy that is being removed from the fuel cell by the cooling water. The "trick" is to compress the air, which compression has a non-trivial energy penalty; and only after compression expose the compressed air to the warm water derived directly or indirectly from the fuel cell coolant. Although this water is only at about 60 deg. C, it is nevertheless able to evaporate into the compressed air, up to the point of saturation. In doing so, it can more than quadruple the mass of the compressed air. This produces extra mass to eventually drive the expander, but almost no energy has been expended to compress this mass. This is because it requires much less energy (work) to compress a liquid to a given pressure than

to compress a gas. The driving force to evaporate the water into the compressed air is the waste heat of the fuel cell.

The "100% efficiency" on p. 17 refers to the recovery of the energy of the extra amount of fuel needed to raise the water-saturated air up to the elevated temperatures needed to heat the reformer and to drive the expander (turbine) efficiently, as opposed to heating only the air without the water. This extra fuel is recovered as additional mechanical energy from the turbine. This recovery, driven by the higher temperature of the heated gas, is in addition to mechanical energy recovered simply because the extra mass impacts the turbine; it is only the latter component that can give a net increase in energy over that required to compress the air. There is a detailed description of the energy recovery on page 17, lines 4 - 21 of the Specification.

Since the system is not ideal, the actual recovery of the energy of burning the fuel is undoubtedly not 100%, but it can theoretically be 100%, because it is not subject to the sort of limitations that require the efficiency of the Carnot cycle, for example, to be less than 100% even in an ideal case.

Applicants thank Examiner for his attempt to give a patentable meaning in accord with his understanding, but the suggestion does not accurately convey what applicants have invented and are intending to patent. In view of the above remarks, it is believed that the Examiner's concerns regarding enablement of Claims 1-65 are overcome, and that the Examiner's enablement rejections should be withdrawn.

In a separate rejection, the Examiner rejected Claim 38 for lack of enablement, asserting that the specification does not reasonably enable the feature of preheating the air/steam mixture before reacting the air/steam mixture. This rejection is respectfully traversed, since exactly this sequence of preheating the air/steam mixture before reacting the mixture is described in the Specification at p. 8, line 14 - 26, and at p. 14, line 26 through p.15, line 24. In Figure 1, the air/steam mixture leaves the fuel cell and is preheated in heat exchange at recuperator 34 and superheater 28, before reacting in the burner 10. During startup conditions, perhaps there would be less pre-heating of the mixture before it is reacted, but as the system approaches normal operating conditions and temperatures, the mixture can be preheated before it is reacted, as clearly described and illustrated in the present Specification.

The Examiner also separately rejected Claim 39 for lack of enablement, on the ground

that the Specification does not reasonably enable using a portion of the air/steam mixture as an oxidant for a fuel cell before evaporating water into pressurized air. This rejection is respectfully traversed on the ground that the limitation of Claim 39 is clearly disclosed and enabled by the present Specification at, for example, p. 14, line 16 through p. 15, line 7, which describes producing an air/steam mixture and using a portion of the mixture as a humidified oxidant in a fuel cell, and then adding additional water to the mixture after it leaves the fuel cell. Although the Examiner is correct that the evaporation of water using waste heat requires that the fuel cell be operating to provide the waste heat, once the system is operational, it can easily operate as recited in Claim 39, as described in the present specification.

B. Indefiniteness Rejections Under 35 U.S.C. §112, ¶2

Independent Claim 1 was rejected for indefiniteness on the ground that it is allegedly unclear which earlier instance of "pressurized air" is being referred to in line 11. The rejection is respectfully traversed.

Claim 1 has been amended to clarify that the "pressurized air" referred to in lines 3 and 6 is the same "pressurized air" referred to in line 11. As discussed above, the cooling water from the fuel cell is evaporated into this pressurized air in order to produce the pressurized air/steam mixture. The reference to the "pressurized air" in line 11 of Claim 1 is to specify that the energy recovered at the expander is in excess of the energy used in compressing air to provide the initial pressurized air stream.

Since Claim 1 as amended is not indefinite, the rejection of the dependent claims is likewise traversed.

C. Anticipation Rejections Under 35 U.S.C. §102

Independent Claims 25 and 28, as well as dependent claims 26, 29-35, 39, 40 and 42 stand rejected as anticipated by Chludzinski. These rejections are respectfully traversed.

Independent Claim 25 recites a method of increasing the efficiency of a fuel cell which comprises converting at least some waste heat of the fuel cell to a pressurized gas/steam mixture by evaporating heated cooling water into a pressurized oxygen-containing gas and passing the gas through the fuel cell as oxidant; heating the gas/steam mixture; passing the heated mixture

through an expander; and recovering mechanical power from the expander in excess of the power absorbed in compressing the pressurized oxygen-containing gas.

Independent Claim 28 recites a method for generating power from fuel cell waste heat which comprises evaporating water into pressurized air using waste heat from a fuel cell to create a pressurized air/steam mixture; reacting the air/steam mixture in a burner to produce a steam-containing exhaust; and driving an expander with the steam-containing exhaust to produce mechanical energy in excess of the energy used to compress the pressurized air.

As noted by the Examiner, Chludzinski describes a fuel cell system having an exhaust air economizer 31. The economizer humidifies the incoming compressed reaction air by equilibration, through a membrane or functional equivalent, with the outgoing cathode exhaust. In other words, water is transferred from the cathode exhaust to the reaction air going into the cathode. This is a way of conserving system water rather than have it lost in the exhaust, and is a common feature of fuel reformers and their combinations with fuel cells. However, Chludzinsky doesn't teach or suggest using fuel cell coolant to humidify the cathode air, as the Examiner appears to suggest. In applicant's system, the air used in the fuel cell is not humidified by equilibration with the fuel cell air (cathode) exhaust, but by equilibration with the fuel cell coolant, or with another fluid in equilibrium with the coolant. Applicant recovers water from the cathode exhaust in heat exchanger 34 and in condenser 36, as water. Unlike the present invention, Chludzinski does not humidify his fuel cell air by injection of fuel cell coolant. The use of fuel cell waste heat as the direct or indirect source of the heated water that is evaporated into compressed air, as recited in Claims 25 and 28, is not taught or suggested by the cited Chludinski reference. In the applicants' system, the evaporation of water into the cathode air is a method of recovering energy. In Chludzinski, only water is being recovered.

Moreover, the removal of moisture from the cathode exhaust, as taught by Chludinski, is fundamentally different from applicant's addition of water to the cathode air stream by equilibration with the fuel cell coolant, either before or after passage of the air through the fuel cell (or both). Indeed, Chludzinsky actually teaches away from the present invention by teaching removal of water from the cathode exhaust stream in at least two locations: at economizer 31, as described above, and at liquid water separator 34, where the liquid water is separated from the exhaust air (see col. 4, line 67 through col. 5, line 5), before the de-watered exhaust is sent to the

expander. As recited in Claims 25 and 28, the present method evaporates additional water into the air stream, using heat from the cooling water, and uses this water-laden air stream to provide excess power from the expander.

On p. 6, line 3 of the office action, the Examiner notes that "the exhaust is also a heat source for fuel reformer [17]." It should be noted that this exhaust is the burner exhaust, from burner 15, as explained by Chludzinski at col 3 lines 9 - 36, especially lines 27-32. This is not the cathode exhaust, which in Chludinski leaves the system through expander 35 without being combusted. Only water, extracted from the exhaust by separator 34, goes to the reformer. In contrast, applicants do convey the cathode exhaust to the burner, where it is combusted and turned into burner exhaust.

Since the reference does not contain every feature of the inventions, it does not properly anticipate the claims, and the rejection is respectfully traversed. Since the independent Claims 25 and 28 are not properly found to be anticipated, the dependent claims, Claims 26, 29-35, 39, 40 and 42, are also not anticipated.

Applicants note that many of the Examiner's statements regarding these dependent claims, particularly on p. 6 of the Office Action, appear to mischaracterize various aspects of the present invention. However, applicant's submit that the meaning of the present claims is clear from the claim language and the Specification, and that the present claims are all novel over the cited Chludzinski reference.

D. Obviousness Rejections Under 35 U.S.C. §103

Claims 36 and 37, which depend from independent Claim 28, were asserted to be obvious over Chludzinski, based on the interpretation of the reference described above. The rejection is respectfully traversed. There is nothing in the reference that would suggest using heat from the fuel cell coolant to evaporate water into the pressurized air supplying the fuel cell. The "exhaust" in Chludzinski that is heating the reformer is not the cathode exhaust, but the burner exhaust, as described above.

Since independent claim 28 does not stand rejected, its dependent claims cannot be obvious over the reference.

Claims 27, 38 and 44 are rejected under §103 as being obvious over Chludinzki in view of

Bloomfield, US 3,976,507. The teachings of the Bloomfield reference suffer from the same deficiency as Chludzinski with respect to the present claims, in that neither reference teaches or suggests using the waste heat of the fuel cell to evaporate water into the pressurized air supply of the fuel cell. In Bloomfield, following the path from compressor 40 through fuel cell anode 36 through line 54 into a heat exchanger 60 and into reactor 46 shows no addition of water by use of the hot fuel cell coolant as a heat source for evaporation.

Since even in combination, Chludzinsky and Bloomfield fail to teach or suggest limitations of the present invention, the rejection is respectfully traversed.

It should be noted that conventionally the term "expander" is used for a class of devices using the expansion of gas to create mechanical energy. Besides turbines, there are other, less common expanders, including scroll types.

E. Information Disclosure Statement

As requested, copies of the references numbered AR and AS in the IDS filed October 1, 2003, together with page 4 of the PTO-1449 form are supplied herewith. Consideration of these references is respectfully requested.

CONCLUSION

In view of the above amendments and remarks, it is believed that all claims are in condition for allowance, and it is respectfully requested that the application be passed to issue. If the Examiner feels that a telephone conference would expedite prosecution of this case, the Examiner is invited to call the undersigned.

Respectfully submitted,

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Dated: 6/23/04

PTO-1449 REPRODUCED	ATTORNEY DOCKET NO.	APPLICATION NO.
INFORMATION DISCLOSURE CITATION IN AN APPLICATION	3402.1000-001	09/870,412
September 8, 2003 (Use several sheets if necessary)	APPLICANT: Lawrence G. Clawson, *et al.*	
	FILING DATE: May 30, 2001	CONFIRMATION NO.: 7092 / GROUP: 1745

		OTHER DOCUMENTS *(Including Author, Title, Date, Pertinent Pages, Etc.)*
	AR	*Fuel Cell Handbook*, 5th ed., pp. 9-37 - 9-38 by USDOE/NETL (Nat'l Energy Tech. Lab) (Oct 2000)
	AS	*Fuel Cell Handbook*, 5th ed., pp. 9-58 - 9-70 by USDOE/NETL (Nat'l Energy Tech. Lab((Oct 2000)
	AT	
	AU	
	AV	
	AW	
	AX	
	AY	
	AZ	
	AR2	
	AS2	
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	AV2	
	AW2	
	AX2	
	AY2	

EXAMINER	DATE CONSIDERED

The high operating temperature of the SOFC puts numerous requirements (phase and conductivity stability, chemical compatibility, and thermal expansion) on material selection and development (41). Many of these problems could be alleviated with lower operating temperatures. However, a high temperature of approximately 1000°C (1830°F), i.e., the present operating temperature, is required in order to have sufficiently high ionic conductivities with the existing materials and configurations (41).

9.2.3 Utilization

Both fuel and oxidant utilizations[52] involve trade-offs with respect to the optimum utilization for a given system. High utilizations are considered desirable (particularly in smaller systems) because they minimize the required fuel and oxidant flow, for a minimum fuel cost and compressor/blower load and size. However, utilizations that are pushed too high result in significant voltage drops. One study (42) cites that low utilizations can be advantageous in large fuel cell power cycles with efficient bottoming cycles because the low utilization improves the performance of the fuel cell and makes more heat available to the bottoming cycle. Like almost all design parameters, the selection of optimum utilizations requires an engineering trade-off that considers the specifics of each case.

Fuel Utilization: High fuel utilization is desirable in small power systems, because in such systems the fuel cell is usually the sole power source. However, because the complete utilization of the fuel is not practical, except for pure H_2 fuel, and other requirements for fuel exist, the selection of utilization represents a balance between other fuel/heat requirements and the impact of utilization on overall performance.

Natural gas systems with endothermic steam reformers often make use of the residual fuel from the anode in a reformer burner. Alternatively, the residual fuel could be combusted prior to a gas expander to boost performance. In an MCFC system, the residual fuel often is combusted to maximize the supply of CO_2 to the cathode while at the same time providing air preheating. In an SOFC system, the residual fuel often is combusted to provide high-temperature air preheating.

The designer has the ability to increase the overall utilization of fuel (or the oxidant) by recycling a portion of the spent stream back to the inlet. This increases the overall utilization while maintaining a lower per pass utilization of reactants within the fuel cell to ensure good cell performance. The disadvantage of recycling is the increased auxiliary power and capital cost of the high temperature recycle fan or blower.

One study by Minkov et al. (42) suggests that low fuel and oxidant utilizations yield the lowest COE in large fuel cell power systems. By varying the fuel cell utilization, the electric power generation split between the fuel cell, steam turbine, and gas turbine are changed. The low fuel utilization decreases the percentage of power from the fuel cell while increasing the fuel cell performance. The increased power output from the gas turbine and steam turbine also results in their improved performance and economy of scale. The specific analysis results depend upon the assumed stack costs. The optimal power production split between the fuel cell and the gas and steam turbines is approximately 35%, 47%, and 17% for a 575 MW MCFC power plant. The

[52]. Utilization - the amount of gases that are reacted within the fuel cell compared to that supplied.

AR

associated fuel utilization is a relatively low 55%. It remains to be seen whether this trend will continue to hold for the improved cells that have been developed since this 1988 report was issued.

Oxidant Utilization: In addition to the obvious trade-off between cell performance and compressor or blower auxiliary power, oxidant flow and utilization in the cell often are determined by other design objectives. For example, in the MCFC and SOFC cells, the oxidant flow is determined by the required cooling. This tends to yield oxidant utilizations that are fairly low (~25%). In a water-cooled PAFC, the oxidant utilization based on cell performance and a minimized auxiliary load and capital cost is in the range of 50 to 70%.

9.2.4 Heat Recovery

Although fuel cells are not heat engines, heat is still produced and must be removed in a fuel cell power system. Depending upon the size of the system, the temperature of the available heat, and the requirements of the particular site, this thermal energy can be either rejected, used to produce steam or hot water, or converted to electricity via a gas turbine or steam bottoming cycle or some combination thereof.

Cogeneration: When small quantities of heat and/or low temperatures typify the waste heat, the heat is either rejected or used to produce hot water or low-pressure steam. For example, in a PAFC cycle where the fuel cell operates at approximately 205°C (400°F), the highest pressure steam that could be produced would be something less than 14 atmospheres (205 psia). This is obviously not practical for a steam turbine bottoming cycle, regardless of the quantity of heat available. At the other end of the spectrum is the TSOFC, which operates at ~1000°C (~1800°F) and often has a cell exhaust temperature of approximately 815°C (1500°F) after air preheating. Gas temperatures of this level are capable of producing steam temperatures in excess of 540°C (1000°F), which makes it more than suitable for a steam bottoming cycle. However, even in an SOFC power system, if the quantity of waste heat is relatively small, the most that would be done with the heat would be to make steam or hot water. In a study performed by Siemens Westinghouse of 50 to 2000 kW TSOFC systems, the waste heat was simply used to generate 8 atmospheres (100 psig) steam (32).

Bottoming Cycle Options: Whenever significant quantities of high-temperature rejected heat are available, a bottoming cycle can add significantly to the overall electric generation efficiency. Should the heat be contained within a high-pressure gas stream, then a gas turbine potentially followed by a heat recovery steam generator and steam turbine should be considered. If the hotgas stream is at low pressure, then a steam bottoming cycle is logical.

If a steam bottoming cycle is appropriate, many design decisions need to be made, including the selection of the turbine cycle (reheat or non-reheat) and the operating conditions. Usually, steam turbines below 100 MW are non-reheat, while turbines above 150 MW are reheat turbines. This generalization is subject to a few exceptions. In fact, a small (83 MW) modern reheat steam turbine went into operation (June 1990) as a part of a gas turbine combined cycle repowering (43).

- the loss in work, or a conversion of "reversible" work from the oxidation process to heat, due to irreversible processes occurring in the operation of the cell.

Heat from these two sources must be rejected from the fuel cell in order to maintain its temperature at a desired level. The heat can be removed and recovered by transferring it across a bounding surface to a heat transfer fluid, but care must be taken to maintain the cell at its desired temperature in this and adjacent regions. Alternatively, heat can be removed in one of the reactant streams passing through the cell -- most practically the air, oxidant stream.

Also in the operation of a practical fuel cell, some unburned fuel must remain in the combustion products leaving the cell in order to maintain a significant generated voltage throughout the cell.

In order to obtain the highest possible efficiency in electrical generation, both the thermal energy in the heat and the unburned fuel rejected from the cell must be recovered and converted into additional electrical energy. This can be accomplished by means of a heat engine cycle making use of a gas turbine operating in a regenerative Brayton or combined Brayton-Rankine cycle or a steam turbine operating in a Rankine cycle. The relative merits of these three heat engine cycles depend on their overall efficiencies and on the practical aspects of integration, operation, and cost of the power generation plant as a whole.

9.3.8 Heat and Fuel Recovery Cycles

Simple representations of three fuel cell based heat and fuel recovery cycles are shown in Figures 9-12, 9-13, and 9-16.

Regenerative Brayton Cycle: The regenerative Brayton cycle, Figure 9-13, shows a gas turbine compressor for the air flow to the cell. The flow then passes through a countercurrent, recuperative heat exchanger to recover heat from the combustion product gases leaving the gas turbine. The air and the fuel streams then pass into the cathode and anode compartments of the fuel cell(s). The air and fuel streams leaving the cell(s) enter the combustor where they mix and the residual fuel burns. The combustion products enter the turbine, expand, and generate additional power. The turbine exhaust gases pass through the recuperative exchanger to the stack.

The most significant variables characterizing the cycle are the fuel cell operating temperature range and the temperature and pressure at the gas turbine expander inlet. These variables are directly related to certain operating variables: the air/fuel ratio entering the fuel cell, the fraction of the fuel leaving the cell unburned, and the temperature difference between the combustion products and air at the high temperature end of the recuperative heat exchanger. The operating variables must be selected and controlled to allow effective operation of the fuel cell, combustor, and gas turbine. There may well be an optimal quantity of unburned fuel leaving the fuel cell, depending on the acceptable fuel cell operating temperature range and turbine inlet temperature.

Further insight can be gained from the idealized T - S diagram for the cycle, Figure 9-14. The compression of the air and fuel streams is represented here as a single adiabatic reversible (constant S) process in which the temperature of the gases rises above ambient. The heating of

AS

- the loss in work, or a conversion of "reversible" work from the oxidation process to heat, due to irreversible processes occurring in the operation of the cell.

Heat from these two sources must be rejected from the fuel cell in order to maintain its temperature at a desired level. The heat can be removed and recovered by transferring it across a bounding surface to a heat transfer fluid, but care must be taken to maintain the cell at its desired temperature in this and adjacent regions. Alternatively, heat can be removed in one of the reactant streams passing through the cell -- most practically the air, oxidant stream.

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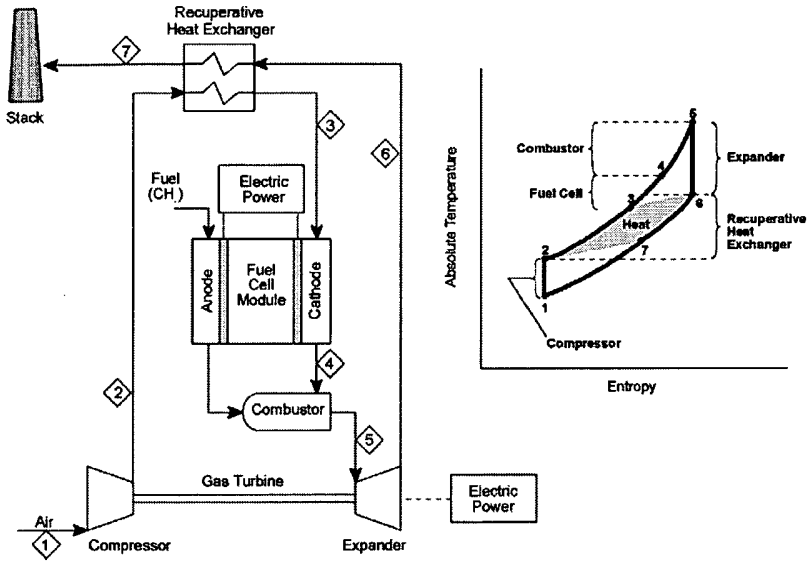

Figure 9-13. Regenerative Brayton Cycle Fuel Cell Power System

the air and also the fuel streams first in the recuperative exchanger, then in the fuel cell and finally in the combustor is assumed to occur along a single line of constant pressure. The subsequent expansion of the combustion gases in the turbine is also represented as an adiabatic reversible (constant S) process in which the temperature of the gases drops to a value close to that of the gases entering the fuel cell. The pressure ratio (PR) of the turbine (and of the compressor) is therefore established by the turbine nozzle inlet temperature (NIT) and the fuel cell operating temperature. In general, the pressure ratio of a regenerative Brayton cycle is low compared with that of a combined Brayton-Rankine cycle. A low pressure ratio allows a low outlet temperature of the exhaust gases from the recuperative exchanger as heat is transferred to the air leaving the compressor (and possibly also the fuel) and consequently results in low heat rejection and a high cycle efficiency.

The practical aspects of the cycle involve the efficiencies of the gas compressors, the turbine expander, and the fuel cell; the pressure losses as the gases flow through the system; and the temperature differences and the difference in heat capacities of the streams flowing through the recuperative heat exchanger. Other aspects of the fuel cell operation must be considered in greater detail for the design and evaluation of the power system. These include the possible need for fuel reforming external to the cell and the recycle of combustion product streams to provide the steam required to carry out the reforming process, to avoid carbon deposition, and to provide H_2 for effective cell operation.

Table 9-23. Performance Calculations for a Pressurized, High Temperature Fuel Cell (SOFC) with a Regenerative Brayton Bottoming Cycle; Approach Delta T=30F

COMPRESSOR EFF =	0.83			n = number of moles				
TURB EXPANDER EFF =	0.89			Cp = specific heat				
FUEL CELL EFF=	56.9			Hf = heat of formation at standard conditions				
CYCLE EFF=	82.1			So = entropy at standard conditions				

STREAM #	1	2	3	4	5	6	7	Cycle
p, PRESSURE, atm	1	1.48	1.48	1.48	1.48	1	1	
T, TEMPERATURE, K	298	337	1200	1311	1332	1216	352	
CH4, n	1	1	1	0.07	0	0	0	
CO, n								
H2, n								
CO2, n	0	0	0	0.93	1	1	1	
H2O, n	0	0	0	1.86	2	2	2	
O2, n	16.23	16.23	16.23	14.37	14.23	14.23	14.23	
N2, n	64.92	64.92	64.92	64.92	64.92	64.92	64.92	
SUM(n)	82.15	82.15	82.15	82.15	82.15	82.15	82.15	
SUM(nCp)	629.72	629.72	629.72	628.97	628.92	628.92	628.92	
SUM(nHf)	-17.9	-17.9	-17.9	-196.181	-209.6	-209.6	-209.6	
SUM(nSo)	3813.11	3813.11	3813.11	3811.99	3811.91	3811.91	3811.91	
GAMMA	1.350				1.351			
Q, HEAT, kcal/molCH4	0.0	543.5	0.0	-0.2	0.0	543.5		1086.8
W, WORK, kcal/molCH4	-24.4	0.0	109.1	0.0	72.7	0.0		157.4

The performance of a solid electrolyte fuel cell (SOFC) system (Hirschenhofer et al., 1994) operating with a regenerative Brayton bottoming cycle for heat and fuel recovery has been calculated. Table 9-23 illustrates the results. The work from the fuel cell burning CH_4 is assumed to be 60% the theoretical maximum; the corresponding fuel cell voltage is 0.63 volts. The efficiencies of the fuel and air compressors are 83%; and the expander of the turbine, 89%. It is assumed that the cell makes direct use of CH_4 fuel, or that oxidation and reforming are coincident; operation of the cell thus provides both the heat and the H_2O required for CH_4 reforming. Pressure losses in the fuel cell, combustor, recuperative exchanger, and the ducts of the system are ignored.

The results of the performance calculations are summarized in Table 9-24. The efficiency of the overall power system, work output divided by the lower heating value (LHV) of the CH_4 fuel, is increased from 57% for the fuel cell alone to 82% for the overall system with a 30 F difference in the recuperative exchanger and to 76% for an 80 F difference. This regenerative Brayton cycle heat rejection and heat-fuel recovery arrangement is perhaps the simplest approach to heat recovery. It makes minimal demands on fuel cell heat removal and gas turbine arrangements, has minimal number of system components, and makes the most of the inherent high efficiency of the fuel cell.

Table 9-24. Performance Computations for Various High Temperature Fuel Cell (SOFC) Heat Recovery Arrangements

General Conditions

SOFC, solid oxide fuel cell

Operating temperature, 1700-1900 F

Fuel cell output: 60% of theoretical maximum from CH4 fuel

Gas turbine compressor, expander efficiences: 83, 89%

Steam turbine efficiency: 90%

Notes

PR = pressure ratio of the gas turbine

NIT = nozzle inlet temperature of the turbine expander

Heat Recovery Arrangement	Work Output, %			Overall System Eff., %	Remarks
	Fuel Cell	Gas Turbine	Steam Turbine		
Regenerative Brayton Cycle	69.3	30.7	n/a	82.1	30 F Approach in Recuperative Exchanger Gas Turbine PR=1.48, NIT=1938 F
Regenerative Brayton Cycle	74.5	25.5		76.3	80 F Approach in Recuperative Exchanger Gas Turbine PR=1.35, NIT=1938 F
Combined Brayton-Rankine Cycl	75.3	10.3	14.3	75.6	Gas Turbine PR=12, NIT=2300 F Steam Turbine: 1600 psia, 1000 F, 1.5" Hg
Rankine Cycle	79.1		20.9	72.4	Steam Turbine: 1600 psia, 1000 F, 1.5" Hg

Combined Brayton-Rankine Cycle: The combined Brayton-Rankine cycle, Figure 9-14, again shows the gas turbine compressor for the air flow to the cell. This flow passes through a heat exchanger in direct contact with the cell; it removes the heat produced in cell operation and maintains cell operation at constant temperature. The air and fuel streams then pass into the cathode and anode compartments of the fuel cell. The separate streams leaving the cell enter the combustor and then the gas turbine. The turbine exhaust flows to the heat recovery steam generator and then to the stack. The steam produced drives the steam turbine. It is then condensed and pumped back to the steam generator.

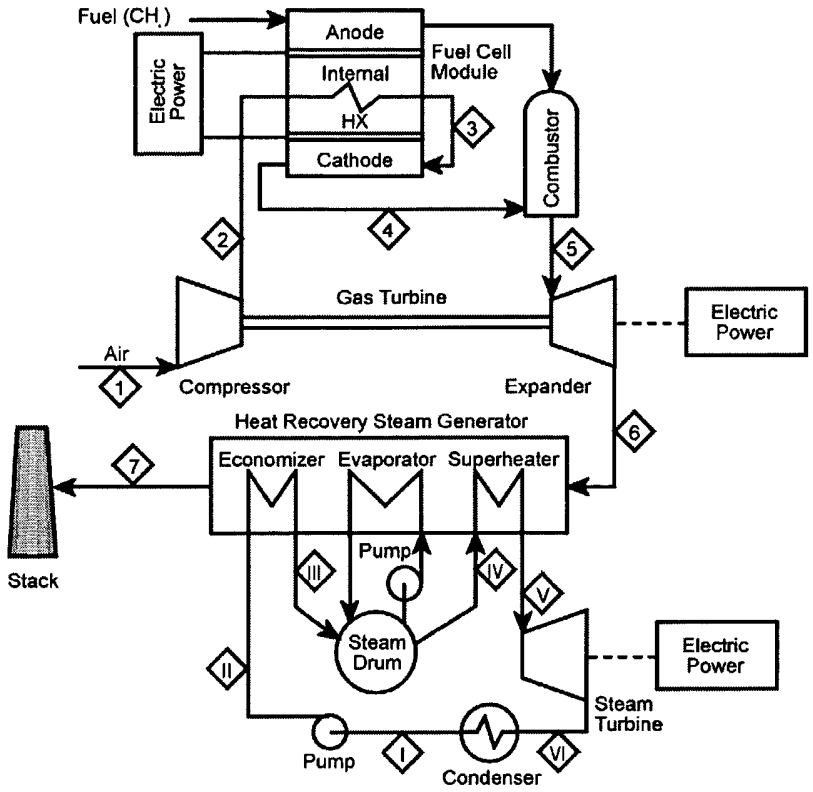

Figure 9-14. Combined Brayton-Rankine Cycle Fuel Cell Power Generation System

The air/fuel ratio entering the fuel cell and the fraction of the CH_4 fuel consumed in the cell are selected to achieve the desired fuel cell operating temperature range and gas turbine NIT and PR. These are selected to correspond with those of a conventional, large-scale, utility gas turbine.

Further insight can be gained from an idealized T- S diagram for the cycle, Figure 9-15, in which both the Brayton and the Rankine cycles are illustrated. Both the pressure and the temperature increase during fuel and air compression in this combined cycle will be significantly greater than in the regenerative Brayton cycle described above. The heating of the air and fuel, the operation of the fuel cell, and the burning of the residual fuel are assumed to occur at constant pressure. The expansion of the combustion product gases in the gas turbine again is represented as an adiabatic, reversible (constant S) process. Next, heat is removed from these gases at nearly constant pressure in the heat recovery steam generator; and they pass out through the stack.

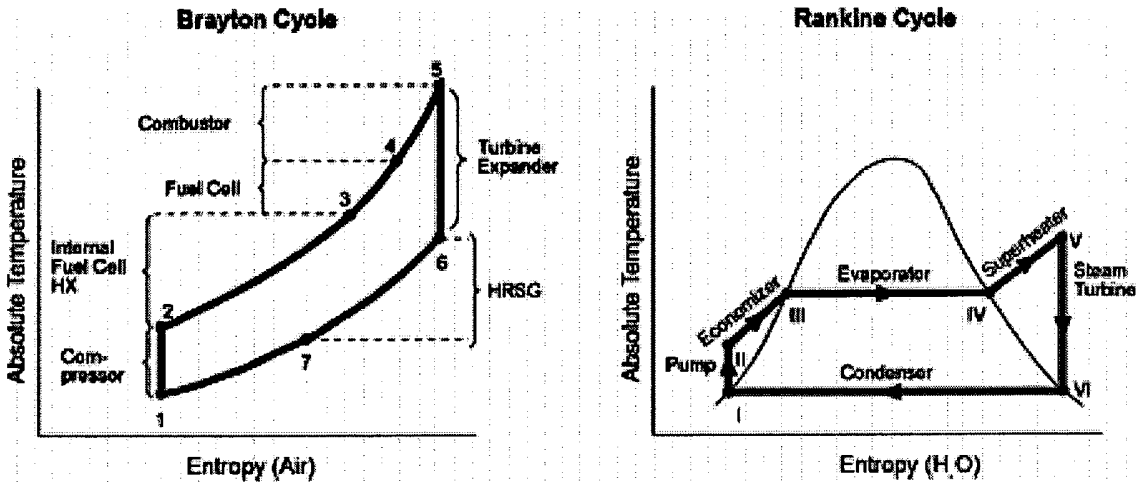

Figure 9-15. Combined Brayton-Rankine Cycle Thermodynamics

The Rankine cycle diagram placed adjacent the Brayton cycle in Figure 9-15 is indicated as a simple steam cycle with superheat, but no reheat and no multi-pressure steam generation. The thermodynamic advantage of the Rankine bottoming cycle is the lowered temperature of heat rejection, in the steam condenser, from the overall combined cycles.

The performance of a SOFC system with a Brayton-Rankine bottoming cycle for heat and fuel recovery has been calculated. Gas turbine compressor and expander efficiencies of 83% and 89% and a steam turbine efficiency of 90% have been assumed.

The significant operating conditions of the gas and steam turbines and the results of the computations are summarized in Table 9-24. The principal result is that the efficiency of the overall system, work output divided by the CH_4 LHV, is increased from 57% for the fuel cell alone to 75% for the overall system. This combined Brayton-Rankine cycle heat-fuel recovery arrangement is significantly more complex and less efficient than the simple regenerative Brayton cycle approach. It does, however, eliminate the requirement for a large, high temperature gas to gas heat exchanger.

The key link between the Brayton and the Rankine cycles is the heat recovery steam generator whose operation is illustrated by the temperature-heat (T-Q) plot in Figure 9-16. The temperatures of the gases and of the water, T, are plotted as a function of the heat, Q, transferred from the combustion product gases to the water-steam between their entrance and any point in the steam generator. The area between the temperature curves for the two flowing streams is an indication of the irreversibility, or loss in available work, resulting from the transfer of heat over a finite temperature difference. Reducing this area, moving the gas and steam curves closer, requires increased heat transfer surface area in the steam generator. Steam reheat and multi-pressure level heat recovery boilers are frequently proposed to minimize the loss in available work.

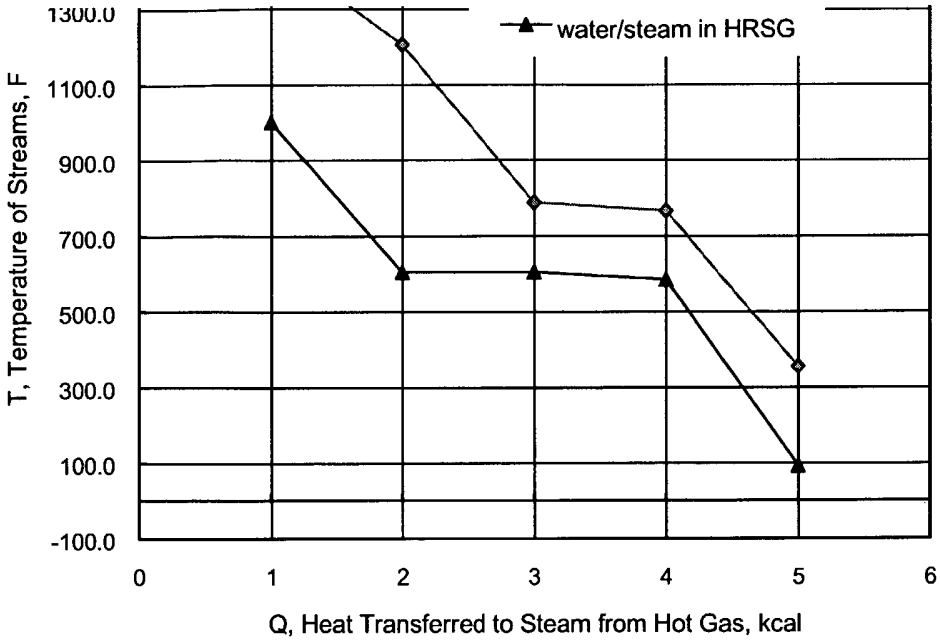

Figure 9-16 T-Q Plot for Heat Recovery Steam Generator (Brayton-Rankine)

Rankine Cycle: The fuel cell Rankine cycle arrangement in Figure 9-17 employs a heat recovery steam generator operating on the exhaust combustion product stream from the fuel cell and combustor at atmospheric pressure. This exhaust stream first provides the heat required to preheat and reform the CH_4 fuel, providing CO and H_2 at temperature to the fuel cell. Partially combusted fuel from the cell is recycled to provide the H_2O required for reforming the fuel. Depleted air from the cell exhaust is recycled to the air feed stream to raise its temperature to the desired value at the cell inlet. The operating conditions and the T - S diagram for the Rankine cycle are identical to those illustrated for the combined Brayton-Rankine cycle in Figure 9-15 and Table 9-24.

The results of the performance calculations for the fuel cell, Rankine cycle heat recovery system, summarized in Table 9-24, indicate that the efficiency of the overall system is increased from 57% for the fuel cell alone to 72% for the overall system. This Rankine cycle heat-fuel recovery arrangement is less complex but less efficient than the combined Brayton-Rankine cycle approach, and more complex and less efficient than the regenerative Brayton approach. It does, however, eliminate the requirement for a large, high temperature gas to gas heat exchanger. And in applications where cogeneration and the supply of heat is desired, it provides a source of steam.

The T - Q plot for the heat transfer processes involved in this fuel cell Rankine cycle arrangement is shown in Figure 9-18. Because heat is removed from the exhaust gases to heat and reform the CH_4 fuel feed, the temperature of the hot gas entering the heat recovery steam generator in this

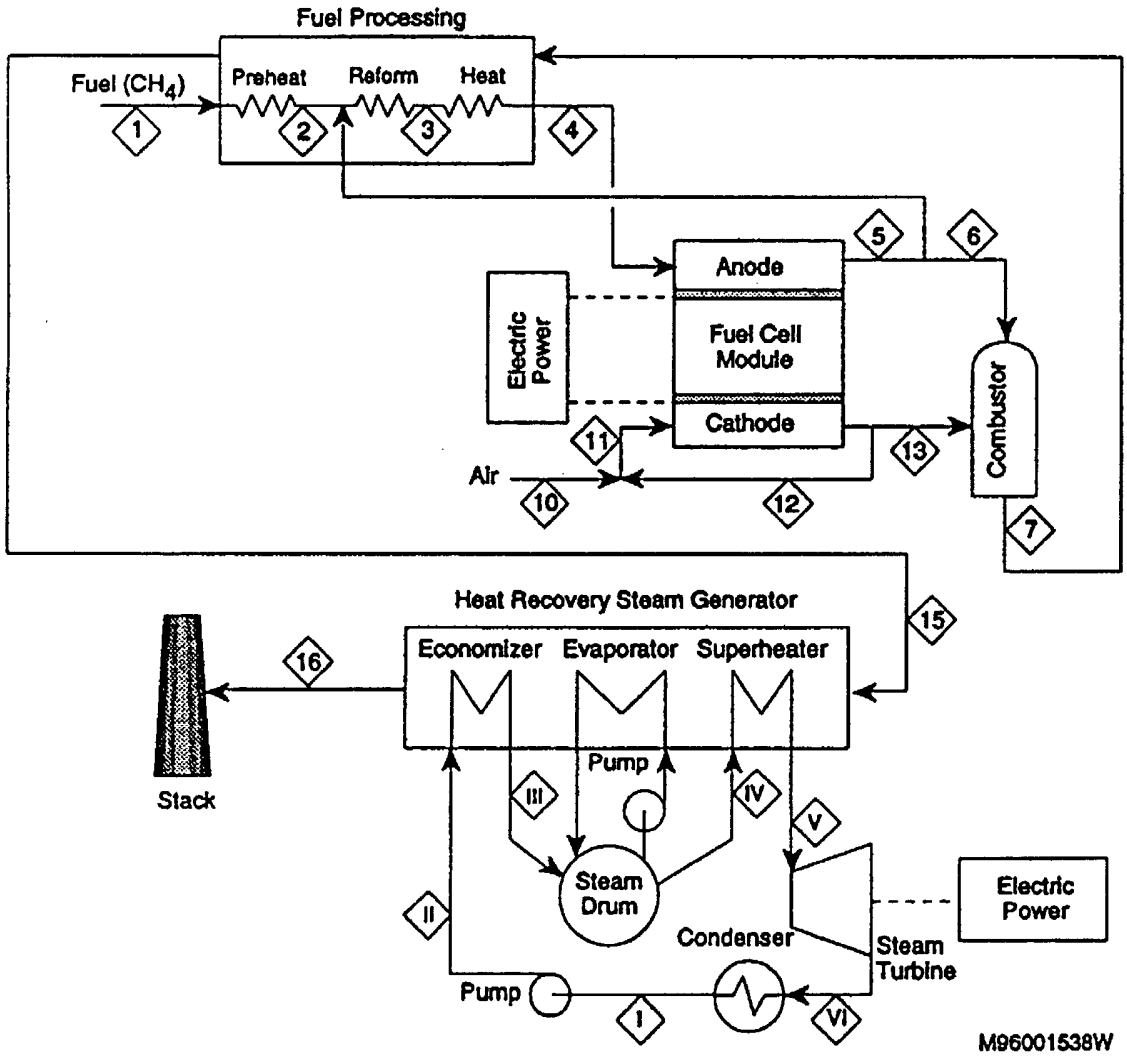

Figure 9-17 Fuel Cell Rankine Cycle Arrangement

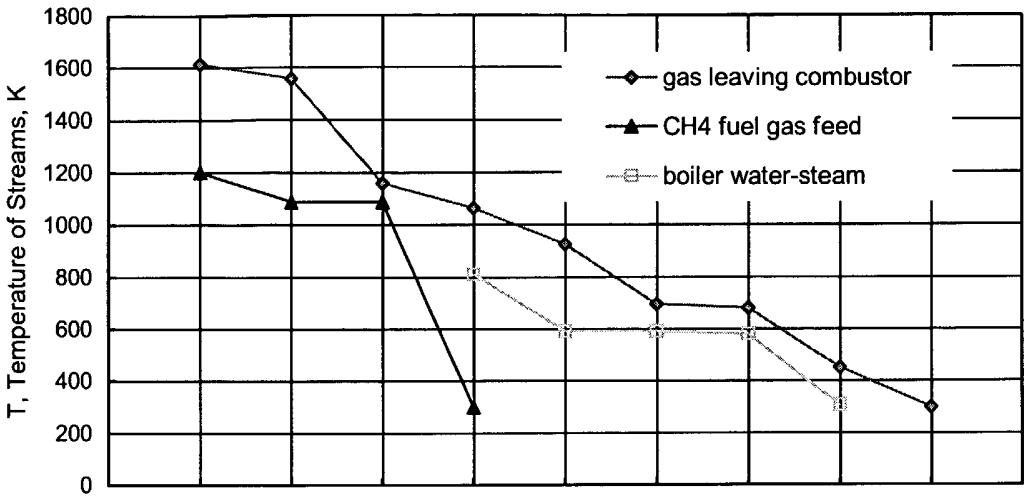

Figure 9-18 T-Q Plot of Heat Recovery from Hot Exhaust Gas

particular Rankine cycle fuel cell arrangement is significantly lower than in the previous combined Brayton-Rankine cycle arrangement. Increased surface area is, therefore, required in the heat recovery steam generator for this fuel cell Rankine cycle arrangement.

These three approaches to reject heat and exhaust fuel recovery with power generation apply primarily to the higher temperature, solid oxide (1800 F) and molten carbonate (1200 F), fuel cell systems operating on CH_4 fuel. The lower operating temperatures of the phosphoric acid (400 F) and polymer electrolyte (175 F) fuel cells severely limit the effectiveness of thermal cycle based power generation as a practical means of heat recovery.

All three of the heat recovery arrangements have calculated overall efficiencies greater that 70% as indicated in Table 9-24. None have been optimized in any sense -- in terms of efficiency, capital and operating costs, maintainability or availability. Each of the arrangements has its advantages and disadvantages. It appears, however, that the regenerative Brayton cycle has the advantage of greatest simplicity and highest potential overall efficiency over the combined Brayton-Rankine and Rankine cycle approaches.

The consideration of heat recovery and use in such fuel cell systems requires some consideration of heat generation and transfer within the cells of the system. Direct oxidation of CH_4 at the anode of the cell, if possible, would implement the overall process:

$$CH_4 + 2O_2 = CO_2 + 2H_2O\ (v)$$

This reaction, having equal number of mols of gas reactants and products, has a negligible change in entropy and thus a negligible heat effect if carried out reversibly at constant temperature. The maximum work available from a fuel cell under these circumstances would then be approximately the enthalpy change of the reaction, i.e., the heat of combustion of the

CH_4; the efficiency of the fuel cell power generation process could, therefore, approach 100%. However, work is lost and a corresponding quantity of heat is produced by irreversibilities both in fuel cell operation --

- the electrical resistance of the electrolyte to ion flow and of the electrodes, current collectors, and leads to electron flow;
- the kinetics of the processes involving reactants, ions, and electrons at the anode and cathode of the cell;
- the transport, or diffusion, of reactants within the anode and cathode chambers to the electrode;
- and also in overall system operation –
- the preheating of the air and fuel streams;
- the pretreating, or reforming, of the CH_4 fuel to provide more reactive H_2 and to prevent the deposition of carbon (C).

The heat resulting from these irreversibilities must then be removed in order to maintain the fuel cells at a desired operating temperature. Irreversibilities and the resulting quantity of heat produced can be reduced, in general, by increasing the active area of the fuel cells, heat exchangers, and fuel reformer; but increased equipment costs result.

In general, reforming of the CH_4 fuel with excess H_2O outside the cell has been practiced both in molten carbonate and solid oxide fuel cell systems in order to produce H_2, more reactive on a fuel cell anode, and to avoid the possible deposition of C. This reforming reaction

$$CH_4 + H_2O = CO + 3H_2$$

is associated with an increase in entropy and absorbs heat. Excess H_2O produces additional H_2 and reduces the CO content of the reformed gases, which may adversely affect anode reactions, by the shift reaction

$$H_2O + CO = H_2 + CO_2.$$

This reaction is thermally neutral. The heat absorbed in the CH_4 reforming reaction is released by the subsequent reaction of the H_2 product at the anode of the fuel cell. If, therefore, the reforming process can be carried out in close proximity to and in thermal contact with the anode process, the thermal neutrality of the overall CH_4 oxidation process can be approximated. And the heat removal and recovery process for the fuel cell system can deal merely with the heat produced by its operational irreversibilities.

Heat removal from fuel cells, and cell batteries, can be accomplished:

- directly through the flow of reactants to and products from them.
- indirectly through heat transfer surfaces in contact with the cell or included within a battery.

A specific fuel cell system is viewed here as having a fixed range of operating temperature between a maximum and minimum; heat must therefore be removed in such a manner to maintain the temperature within these limiting values. If heat is removed directly by reactant flows, then the quantity of flow must be adjusted so that inlet and outlet temperatures (as well as

the intermediate temperatures) of the cell and of the flow streams are within the permissible range. Practically, the air stream is adjusted to achieve this result, since the purpose of the fuel cell is to consume the fuel in the production of electrical energy. Increasing the fuel flow to remove heat from the cell increases the quantity of unburned fuel in the exhaust from the cell. If heat is removed from the fuel cell indirectly through adjacent or embedded surface, then the flow and temperature of the coolant stream can be selected somewhat independent of the cell operating temperature. But the distribution of heat transfer surface in the cell (or battery) and the rate of heat transfer across that surface must be carefully adjusted and controlled to maintain the temperature throughout the cell (or battery) within the prescribed temperature range.

The regenerative Brayton cycle, as presented, depends primarily on its fuel cell component for conversion of the fuel and thus for its overall efficiency. The gas turbine merely provides the means for recovery of the waste heat and residual fuel in the combustion product stream. The gas turbine operates, therefore, at a temperature only slightly elevated above that of the cell by the combustion of the residual fuel. The pressure ratio selected for the turbine in this regenerative cycle is determined by the ratio of the temperature of the gases leaving the auxiliary combustor to the temperature of the reactant gases entering the fuel cell. In general, for either molten carbonate or solid oxide cells, this selected pressure ratio will be less than two. The proposed method of cell cooling is air flow, which will be increased significantly, by a factor of 4-8 above that required for oxidation of the fuel. The feasibility of this cycle will depend on the availability of air compressor and turbine expander units with:

- the pressure ratio and temperature capability compatible with the fuel cell operation.
- a capacity appropriate to market applications.

The effectiveness of the regenerative Brayton cycle performance will depend on the efficiency of the fuel cell, compressor, and turbine units; the pressure loss of gases flowing through the system; the approach temperatures reached in the recuperative exchanger; and, most importantly, the cost of the overall system.

The combined Brayton-Rankine cycle depends on both the fuel cell and the gas turbine components for conversion of the fuel and thus for its overall efficiency. The extent of conversion of the fuel occurring in the fuel cell increases as the cell operating temperature and the range of coolant temperature rise increase. For this reason, the cycle as presented is based on indirect heat removal from the cell, heating the air stream temperature from the compressor outlet to the cell operating temperature. This provision maximizes the cell contribution to the energy output of the combined cycle. The PR and NIT of the turbine are those selected to match those of the current utility scale equipment -- a PR of 12 and an NIT of 2300 F -- resulting in a combined cycle efficiency of perhaps 45-50%, not considering the electrical energy output of and the fuel input to the fuel cell. The fuel combustion occurring in the combustor and overall air/fuel ratio is then determined by the combination of the cell and the turbine inlet temperatures.

The fuel cell Rankine cycle arrangement has been selected so that all fuel preheating and reforming are carried out external to the cell and air preheating is accomplished by mixing with recycled depleted air. The air feed flow is adjusted so that no heat transfer is required in the cell or from the recycled air. Consequently, the internal fuel cell structure is greatly simplified, and the requirement for a heat exchanger in the recycle air stream is eliminated.

Summary

Advantages, Disadvantages of Various Fuel Cell, Power Cycles

Regenerative Brayton

Advantages:

- simple cycle arrangement, minimum number of components.
- relatively low compressor and turbine pressure ratio, simple machines.
- relatively low fuel cell operating pressure, avoiding the problems caused by anode/cathode pressure differential and high pressure housing and piping.
- relatively low turbine inlet temperatures, perhaps 1950 F for solid oxide and 1450 F for molten carbonate fuel cell systems. Turbine rotor blade cooling may not be required.
- relatively simple heat removal arrangements in fuel cells, accomplished by excess air flow. No internal heat transfer surface required for heat removal.
- fuel conversion in cells maximized, taking full advantage of fuel cell efficiency.
- adaptability to small scale power generation systems.

Disadvantages:

- tailoring of compressor and turbine equipment to fuel cell temperature and cycle operating pressure required. (It is not clear to what extent available engine supercharging and industrial compressor and turbine equipment can be adapted to this application.)
- large gas to gas heat exchanger for high temperature heat recuperation required.
- efficiency and work output of the cycle sensitive to cell, compressor, and turbine efficiencies; pressure losses; and temperature differentials.

Combined Brayton-Rankine

Advantages:

- integrated plant and equipment available for adaptation to fuel cell heat recovery.
- high efficiency system for heat recovery.

Disadvantages:

- complex, multi component, large scale system for heat recovery.
- adaptation of existing gas turbine required to provide for air take off and return of hot depleted air and partially burned fuel.
- high pressure operation of the bulky fuel cell system required.
- precise balancing of anode and cathode pressures required to prevent rupture of fuel cell electrolyte.
- indirect heat removal required from fuel cells with compressed air, initially at low temperature, to enable significant conversion of the fuel flow in the cells.

Rankine

Advantages:

- ambient pressure operation within the fuel cell.
- heat recovery in a boiler, avoiding the high temperature gas to gas exchanger of a regenerative Brayton cycle.
- no gas turbine required, only fans for air and exhaust product gas flow.

- steam available for cogeneration applications requiring heat.

Disadvantages:

- inherently lower efficiency than regenerative Brayton and combined Brayton-Rankine cycles.
- requirement for cooling and feed water.
- greater complexity than regenerative Brayton cycle arrangement.

9.4 Fuel Cell Networks

9.4.1 Molten Carbonate Fuel Cell Networks: Principles, Analysis and Performance

The U.S. Department of Energy's National Energy Technology Laboratory (NETL) sponsors the research and development of engineered systems which utilize domestic fuel supplies while achieving high efficiency, economy and environmental performance. One of the most promising electric power generation systems currently being sponsored by NETL is the molten carbonate fuel cell (MCFC).

NETL looked at improving upon conventional MCFC system designs, in which multiple stacks are typically arranged in parallel with regard to the flow of reactant streams. As illustrated in Figure 9-19a, the initial oxidant and fuel feeds are divided into equal streams which flow in parallel through the fuel cell stacks.

In an improved design, called an MCFC network, reactant streams are ducted such that they are fed and recycled among multiple MCFC stacks in series. Figure 9-19b illustrates how the reactant streams in a fuel cell network flow in series from stack to stack. By networking fuel cell stacks, increased efficiency, improved thermal balance, and higher total reactant utilizations can be achieved. Networking also allows reactant streams to be conditioned at different stages of utilization. Between stacks, heat can be removed, streams can be mixed, and additional streams can be injected.

Stacks in series approach reversibility. MCFC stack networks produce more power than conventional configurations because they more closely approximate a reversible process. To illustrate this fact, consider Figure 9-20, which compares the maximum power that could be generated by three different MCFC systems having identical feed stream compositions[1].